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DESIGN OF A BOTTOM IMPERMEABLE BARRIER

IN CONJUNCTION WITH

A CONTAMINATED SITE CONTAINMENT STRUCTURE

by

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1.0 INTRODUCTION

1.1 Background

With numerous sites contaminated with hazardous wastes that have leaked or spilled into the surrounding soils, site owners are exploring for the most cost effective means of site confinement and remediation of contamination. Usually when confronted with the problem of a contaminated site, the owner has one of four options (Rumer et al., 1993):

A. Cleanup of the contaminated site by treating the waste

B. Stabilization of the waste within the contaminated soil, immobilizing the contaminant, thus reducing the risks to the surrounding environment

C. Containing the contaminants by construction of a low permeability barrier around the site

D. Or any combination of the above methods.

The containment structure is a preferred means to prevent the spread of contaminants further into the surrounding

soils or, more often, into the ground water source.

The use of a containment structure started with the construction of vertical seepage barriers, most often under dams. These were used to slow the flow of water under the structure to improve the structure's stability. At waste sites, the first barriers used were vertical walls, usually some type of slurry wall. The slurry walls were placed up-gradient from the site to divert flow around the site. Often, pumping of the ground water down-gradient in conjunction with the vertical barriers is used to assist the diversion of flow. However, while vertical walls could help prevent the ground water from coming into direct contact with the source of contamination, they do not prevent the contaminants from flowing deeper into ground, where the contaminants may eventually come into contact with the ground water. Construction of a cap will also help in slowing the percolation of contaminants down into the ground water, but will not prevent significant migration of existing contaminated liquids.

The need for a bottom barrier to complete the containment structure is currently recognized. The complete containment structure is shown in Figure 1-1. Several years ago, very little material was published on

the subject. Today, the topic is being discussed in several publications, and several companies have designed systems to construct a bottom barrier.
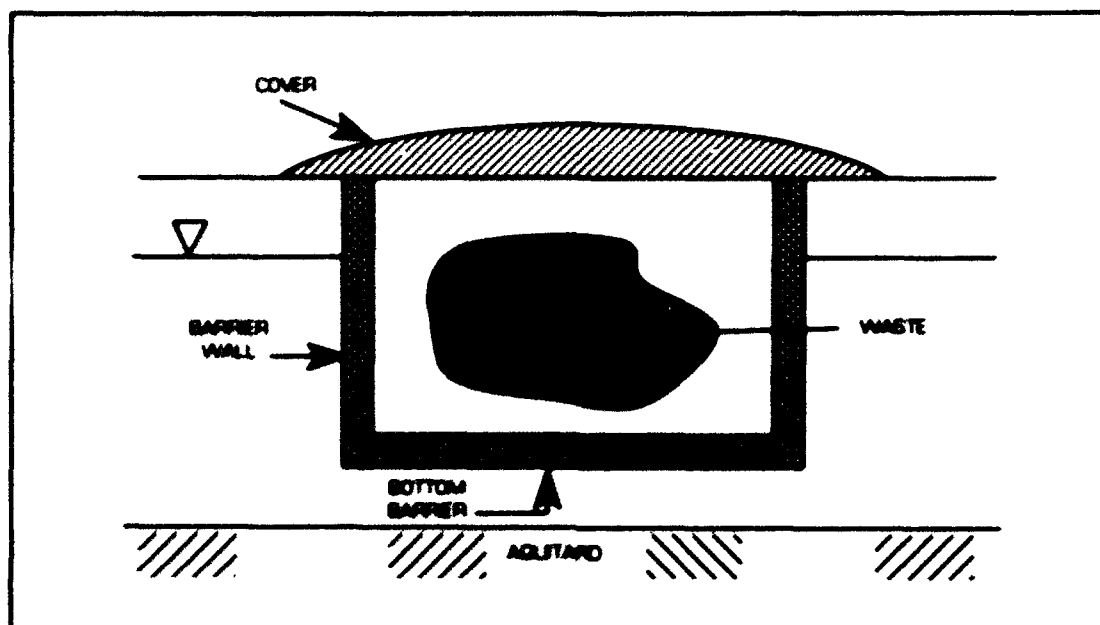
Figure 1·1

Although the containment structure is often thought as being impermeable, construction of a totally impermeable structure is not possible. Construction of extremely low permeability is specified. One measure of permeability that most waste containments attempt to achieve is the Environmental Protection Agency's standard for the cap and bottom barrier of waste disposal sites of 1×10^{-7} cm/sec. Often, active moisture control measures, such as extraction and injection wells, are used inside the containment to further reduce the migration of

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contaminants out of the structure.

In designing the bottom barrier, the designer must evaluate the follow criteria prior to final design of the bottom barrier:

-The type of boring that will be utilized to maximize grouting efficiency and minimize site disturbance.

-The grouting technique that will be utilized in order to maximize the effectiveness of the grout.

-The type of grout, and its particle composition.

-The construction scheme that will be used to maximize the grouting efficiency and placement.

When designing the bottom barrier, all of these criteria interact with the other.

Perhaps one of the most difficult decisions involves selecting a proper grout. When selecting the grout, the designer must not only consider the grout's resistance to the contaminants and the soil-water chemistry, but must also be concerned with the grout's viscosity, set-up

time, strength, stability, among other factors. All of
these factors interact to make up a grout that will
properly fill the required soil, withstand the overburden
pressure, and resist deterioration when permeated with
ground water and contaminants.

While several published schemes have been proposed,
the actual construction of a bottom barrier is a
relatively new technique. Although, the technologies
needed to construct a bottom barrier are readily
available from other fields. Concisely bringing together
all of the other technologies is the key in constructing
a bottom barrier. Finally, before a designer or
environmental engineer decides to install a containment
structure, he should take into account the following
considerations (Rumer et al., 1993):

> -knowledge of the hydrological conditions of
> the site
> -advantages, limitations, and costs associated
> with the various containment options
> -compatibility of the containment materials
> with the groundwater and the contaminants at
> the site
> -implementing quality control and assurance

methods during the construction of the
containment

-designing and installing appropriate
monitoring systems for evaluating the
effectiveness of the containment

-methods of repair and modifications that may
be required during the lifetime of the
containment.

1.2 Purpose and Scope

The purpose of this report is to provide an
assessment of the different techniques and considerations
that must be taken into account when attempting to
construct a bottom barrier. The bottom barrier is an
integral part of a total containment system, that is
designed to prevent the spread and migration of
contaminants away from its source, and into the
surrounding soils or groundwater. When designing the
bottom barrier, one must take into account the
construction scheme, the type of boring used, the type of
grout, and the grouting technique. All of these factors
interact and must be considered together when designing
the bottom barrier.

2.0 BORING AND GROUTING TECHNIQUES

2.1 Boring Techniques

When attempting to construct an impermeable bottom barrier, one must first decide on which method of boring and grout injection to utilize. Basically, there are five methods to bore in order to construct the bottom barrier: vertical drilling, horizontal drilling, inclined drilling, directional drilling, and microtunneling. Vertical drilling will not be discussed further due to the fact that this technique involves drilling through and disturbing the area of the contamination, which would be best left undisturbed.

The four types of drilling that will be considered in this report are summarized below:

Drilling Method:	Horizontal	Inclined	Directional	Micro-Tunneling
Maximum Diameter:	7 Ft.	10 Ft.	4 Ft.	10 Ft.
Access Area:	Grouting Gallery	Surface	Surface	Jacking Pit
Maximum Depth:	550 Ft.	150 Ft.	6000 Ft.	750 Ft.

All four methods provide adequate coverage and depth to
be effective for installing a bottom barrier at a variety
of sites. However, the principal difficulties in
utilizing this technology lies in effective control of
placement and control of the injection holes and
providing machine access.

2.1.1 Horizontal Drilling

For horizontal drilling, access for machinery must
be provided through an excavated pit, usually excavated
to the level of proposed installation. Often a parallel
pit, called the exit pit, is cut where the grouting ends.
Most horizontal boring methods are considered non-
steerable, although the vertical alignment can be changed
during the boring process. The horizontal alignment can
also be changed, and is dependent on the initial ground
conditions. The two principal types of horizontal
drilling include the auger method and the slurry method
(Baker et al., 1992).

The auger method consists of jacking a casing into
the borehole from the access pit, while continually
augering out the soil. No slurry is used or needed, and
the soil is removed out of the access hole. Auger
flights are added, until the auger reaches the exit pit,

where the flights are removed and the grouting casing can
be installed. The auger method can cut holes up to seven
feet in diameter to a length of over 550 feet (Baker et
al., 1992).

The slurry method utilizes drill bits and tubing to
cut through the soil. Unlike the auger method, a slurry
mixture is used to keep the drill bit clean and assist in
spoil removal. Unlike jet grouting, the slurry is not
used to cut the face of the tunnel; this is done
mechanically. Proper disposal of contaminated material
is more difficult with the slurry mix, since the slurry
mix increases the amount of material that has to disposed
of as contaminated waste.

2.1.2 Inclined Drilling

For inclined drilling, much of today's technology
for vertical drilling can be applied. In the same
fashion as using a deep soil mixing system to form a
bentonite cutoff wall, these walls can be drilled from
the surface at an angle to form a conically shaped
barrier. Current technology limits this specific
technique to a depth of 150 feet. Use of other methods
of inclined drilling would be virtually unlimited in
depth. Techniques described in drilling from the
horizontal and directional drilling can be applied to

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inclined drilling. While inclined drilling may appear to be a reasonable solution, greater difficulties exist with confirming the accuracy of keying the formation together, since small deviations in the angle of drilling will magnify themselves at depth.

2.1.3 Small Diameter Directional Drilling

Directional drilling holds promise for constructing an "impermeable" bottom barrier. Many have successfully used this technique to guide borings under river crossing and other obstacles. Basically, directional drilling consists of both small diameter drilling and large diameter drilling.

Small diameter directional drilling consists of boring diameters of up to 8 inches, with a maximum penetration of 550 feet. While several different methods are available for locating and determining the boring head depth and location, most units contain a transmitter that sends the driller the primary information, along with the head's attitude. The driller uses this information to steer the head by employing one of the following techniques:

a. Displacement/compaction (rod pushing)

b. Hydro-jet drilling

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c. Pneumatic, rotary air drilling

The first system incorporates a tapered head that is used in displaceable soils. As the head is pushed through the soil, the taper on the head is used to steer the rod. The head will pull the rods in the direction of the alignment of the taper, where the rod must be rotated to maintain a straight path.

In hydro-jet drilling, the system works along the same principles, except that instead of a tapered head, the system uses jetting nozzles that are aligned on one side the steering head. By jetting a mixture of water and drilling mud, usually bentonite, the hole is bored out. Again, as with rod-pushing, the rod must be rotated to maintain a straight path, with the bore steering in the direction of the side of the jet nozzles.

The pneumatic and rotary air drilling systems are used for only stiff soils or rock. The pneumatic piercing tool has a tapered head like that used in rod pushing. While the air rotary drill head is steered by rotating the cutting tool independently, it allows the drill stem to be pushed forward without rotating. All of these systems utilize a two-way radio to communicate information and commands, and are pulled back to the

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entrance pit after completing the tunnel. (Baker et al., 1992)

The difficulty in using small diameter directional drilling in soft soil conditions was demonstrated by installation of a deep monitoring well under Williams Air Force Base, near Phoenix. After two unsuccessful tries, a well was finally installed that was located 230 feet deep, and over 2,300 feet long. The hole that was drilled was only 0.9 inches in diameter, and was to be reamed to about 1.8 inches. The hole was constructed using hydro-jet drilling. The location and depth of the device was determined through a downhole magnetic guidance system, and was confirmed by applying an electrical current to the wire loop on the surface and measuring the magnetic field around the location. However, large discrepancies between these two methods forced utilization of a third method, a gyro tool down hole. Using three methods, they were able to measure the position with an accuracy of three feet.

Borehole instability forced the construction to be continuous, 24 hours a day, with quick installation of the monitoring well. While no costs were reported, the large number of attempts and problems with the drilling apparatus becoming stuck would certainly lead one to

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believe that this technique needs further refinement before being utilized on a large scale. (Oakley, 1993)

2.1.4 Large Diameter Directional Drilling

Large diameter directional drilling utilizes many of the same techniques as the small diameter drilling. Large diameter drilling can excavate openings up to 48 inches in diameter, penetrating 6000 feet (Baker et al., 1992). Large diameter drilling requires much more working space and highly sophisticated communication and instrumentation, since small path deviations are not tolerable. For soils, use of hydro-jet and air rotary drilling techniques have been used successfully. Often to get the proper diameter hole, the hole will be reamed from two to three times its original diameter. As with the small directional drilling technique, this system can be utilized without requiring any surface excavation.

2.1.5 Microtunneling

A discussion of the different options available for constructing a bottom layer would be incomplete without consideration of today's microtunneling technology. Public work specialists view microtunneling as one of today's most promising technologies. In fact, the United States has greatly lagged behind Europe in applying this

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new technology. Although, much has been written and researched on microtunneling, most of the research has been primarily directed towards replacement or installation of underground utilities. This has led to much of the written work and applications concentrating on pipe-jacking in conjunction with microtunneling.

Microtunneling is primarily a horizontal drilling method that utilizes a highly sophisticated laser-guided, remote controlled system, and can be employed in almost any soil condition. The tunnel can be constructed with a high degree of accuracy (± 1 inch). Microtunneling requires the excavation of a primary jacking pit. The components of the microtunneling system consist of:

a. The Mechanized Excavation System: The excavation system is composed of the cutter head mounted on the boring machine's face, and is powered by motors located in the machine. The machines have cutting faces with unique tools for cutting through a silty soil to cutting rock with unconfined compressive strength up to 30,000 psi. The boring machine also incorporates the steering unit.

b. The Guidance Control System: As mentioned, this system is guided by laser, which provides the

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grade information and alignment for the machine to follow. The control system that receives the information on the alignment of the laser can be either an active or passive system.

c. The Propulsion System: The microtunneling process is a pipe jacking process that consists of a jacking frame and jacks in the drive shaft. As the unit is jacked in, a new length of pipe is added, and the jacking continues.

d. Spoil Removal System: Like the horizontal boring systems, microtunneling uses two different types of spoil removal; slurry transportation, and auger transportation. In the slurry system, the spoil is mixed into a slurry in a container behind the cutting head of the boring machine, and is then hydraulically removed through discharge pipes that run along the inside of the jacked pipe or casing. The slurry can be disposed of, or more commonly separated so that the slurry can be re-used and the spoil separated. The auger system uses an independent auger system enclosed in a pipe that also runs along the inside of the jacked pipe or casing. The spoil is augured to the drive shaft, collected, and disposed.

e. Control System: The control system allows the operator to remain completely informed of the drilling process, and to modify the process as needed. Often including a closed-circuit television, the electronic information is relayed to the operator, where the level of control can run from completely automatic to completely manual. Recording of data is also allowed electronically.

f. Pipe Lubrication System: A pipe lubrication system is often recommended for large diameter pipes or pipes with a long run. Often, the pipes have several small perforations that allow access to inject the lubricant. The exterior system consists of a mixing tank and pumping equipment. The lubrication system can reduce the total thrust needed to jack the pipe and reduce the stress that the pipe must withstand.

The cutting head of the microtunneling system is jacked ahead of the pipes or temporary casing, which is also needed for tunnel stability. Microtunneling can penetrate to 750 feet, and is capable of drilling holes up to 10 feet in diameter utilizing the slurry system and only up to 3.5 feet for the auger system. (Iseley, 1993)

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2.2 Grouting Techniques

Now that the different methods of boring and tunneling that could be best utilized in constructing a bottom barrier have been reviewed, the different grouting types and techniques will be considered. There are five different types of grouting, which include:

    a. Intrusion Grouting

    b. Displacement Grouting

    c. Permeation Grouting

    d. Fracture Grouting

    e. Replacement Grouting

2.2.1 Intrusion Grouting

While grouting has been used for centuries, it wasn't until the early twentieth century that grouting began to be used in the United States. Initial use was for primarily for sealing foundations under dams. Once pumps were developed that were capable of injecting slurry grouts beneath major dams, the use of grouting began to expand. Intrusion grouting, using a slurry grout, was the first type of grouting that was heavily utilized, and was primarily used to reduce the

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permeability beneath civil structures by filling existing seams and fractures in rock formations. For construction of bottom barriers, this technology would not be used unless a fractured low hydraulic conductivity formation already existed beneath the site. Again, the use of this technology would have to be closely monitored because of the difficulty in verifying that the secondary porosity features had all indeed been plugged.

2.2.2 Displacement Grouting

Displacement grouting, which is also called compaction grouting, utilizes a very low slump cement-based grout which is injected under high pressure. By injecting under pressure, the grout compacts and displaces the adjacent soil, and forms a homogenous grout bulb. The technology is primarily used to improve soil stability, reduce compressibility, and increase bearing capacity. Compaction grouting has been used as a pre-construction technique to reduce settlement of structures, and to minimize settlement from soft ground tunneling. Compaction grouting has also been used in increasing the volume of space in municipal solid waste landfills by using finely ground waste, fly or bottom ash, dredge spoils, or sewage sludge as grout (Mitchell, 1992). Compaction grouting is rarely used for low

permeability or saturated soils, because the sudden
pressure application does not allow for quick pore
pressure dissipation.

2.2.3 Permeation Grouting

Permeation grouting is dependent on the soil's
primary porosity to allow an adequate amount of grout to
fill the voids between the soil particles, and to fill or
form a bond between these voids. Permeation grouting may
involve either chemical grouts or cement grouts.
Chemical grouts use a bond to seal the voids and improve
the soil's strength. Chemical grouts can have a gel time
that can be controlled and set to last from minutes to
hours, depending on the soil and depth of penetration
that is desired. Chemical grouting gained widespread
acceptance in the 1970's; however, environmental and
worker safety concerns have slowed this industry's
growth. A discussion on the viability of chemical grouts
in hazardous waste sites is included in Chapter 3 of this
report. Chemical grouts are considered poor choices for
soils with high permeability, since these grouts require
a small pore space in order to form a bond.

Permeation grouting can also be used with cement-
treated grouts if the permeability of the soil is fairly
high, usually greater than .01 m/s (Karol, 1990). There

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are two main methods of permeation grouting: point injection and sleeve pipe. In the point injection method, the casing is driven to full depth, and then withdrawn to the desired point of grouting, where the grout is applied. In the sleeve pipe method, or also called tube-a-manchette, the sleeve pipe is installed in the grout hole, and sealed in place with a weak cement grout in the annular space. The sleeve pipe has openings at about one foot intervals. These openings have a rubber covering over them that acts as a one-way valve, allowing grout out of the pipe, but not back into the sleeve. A grouting tube with double packer is used to inject the grout. Hydraulic fracturing occurs in the annular seal so that the grout can penetrate the adjacent formation. The tube-a-manchette has several advantages. The grout may be re-applied if results are not satisfactory, and different grouts may be applied with the grouting tube. Finally, multiple grouting can be performed in the same sections. (Rumer, 1993)
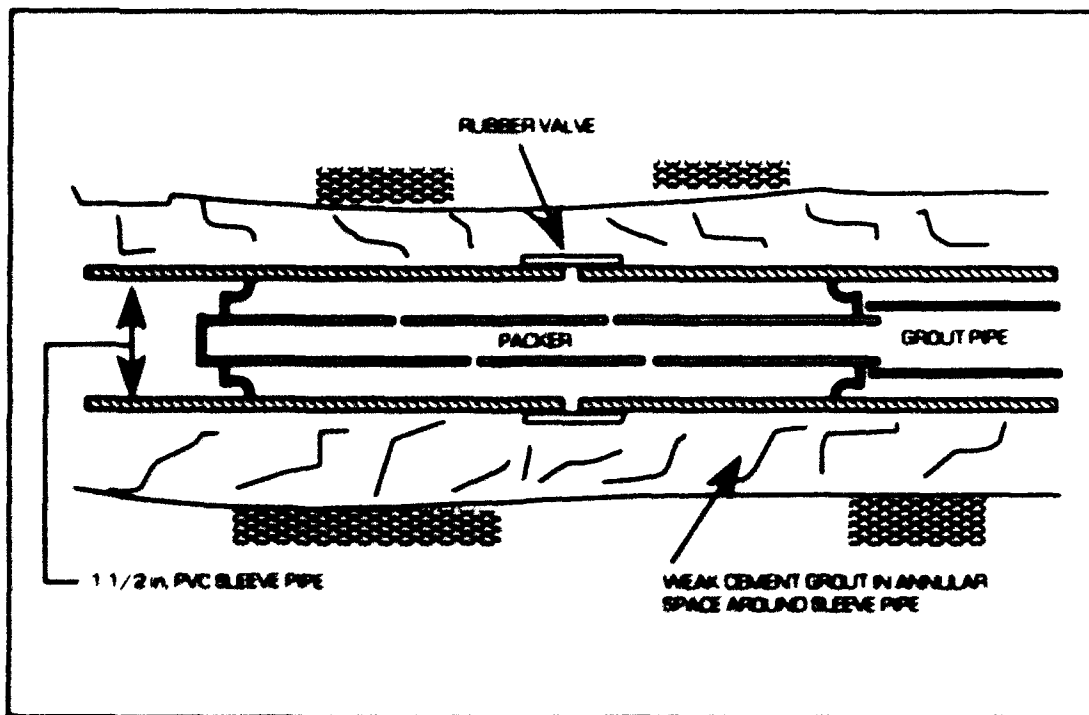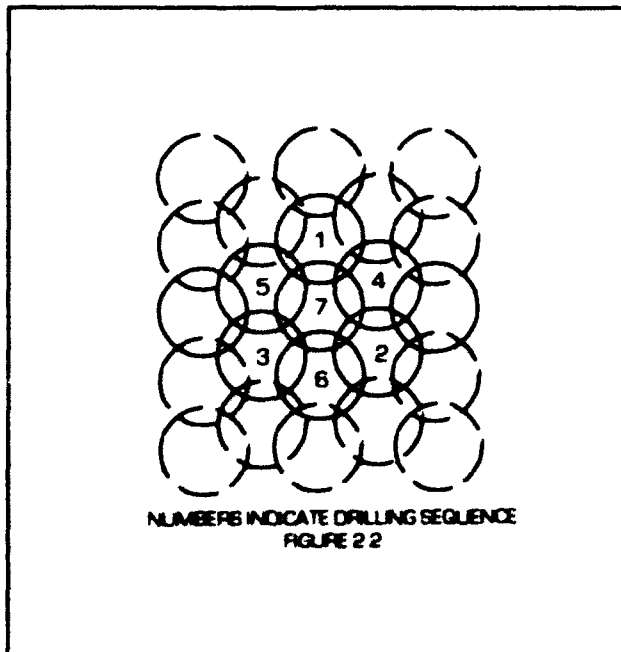
Figure 2-1

Permeation grouting has been successfully used to create vertical barrier walls, although at least two, but preferably three, adjacent rows must be grouted to achieve the desired result. In addition, care must be taken to drill the grout holes in proper sequence and

NUMBERS INDICATE DRILLING SEQUENCE
FIGURE 2.2

position. A typical drilling layout and sequence is shown.

While permeation grouting can be used, the largest drawback is that the placement of the grout cannot be controlled well enough to insure a complete seal.

2.2.4 Fracture Grouting

Fracture grouting has been used to stabilize soils that are weak. This technique is used only in impermeable soils. Pressure injection is used to "fracture" the soil, and create new zones of secondary porosity that are pressure filled with the grout. This technique is used to reinforce weak soils and cause a controlled up-lifting of settled structures. A variation of this technique, called the Block Displacement Method, was unsuccessfully used to create a bottom barrier. The test on this Block Displacement Method showed the difficulty in controlling the fractures such that they permeate all the way through the blocks of soil displaced

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(Rumer, 1993). Fracture grouting has very limited value in constructing a bottom barrier, and will not be discussed any further.

2.2.5 Replacement Grouting

The final method of grouting, replacement grouting, shows the greatest degree of promise in attempting to construct a bottom barrier. Replacement grouting, more commonly called jet grouting, has been used abroad for over twenty years, but has only recently been attempted in the United States. There are three basic systems of jet grouting:

    a.   Single Rod

    b.   Double Rod

    c.   Triple Rod
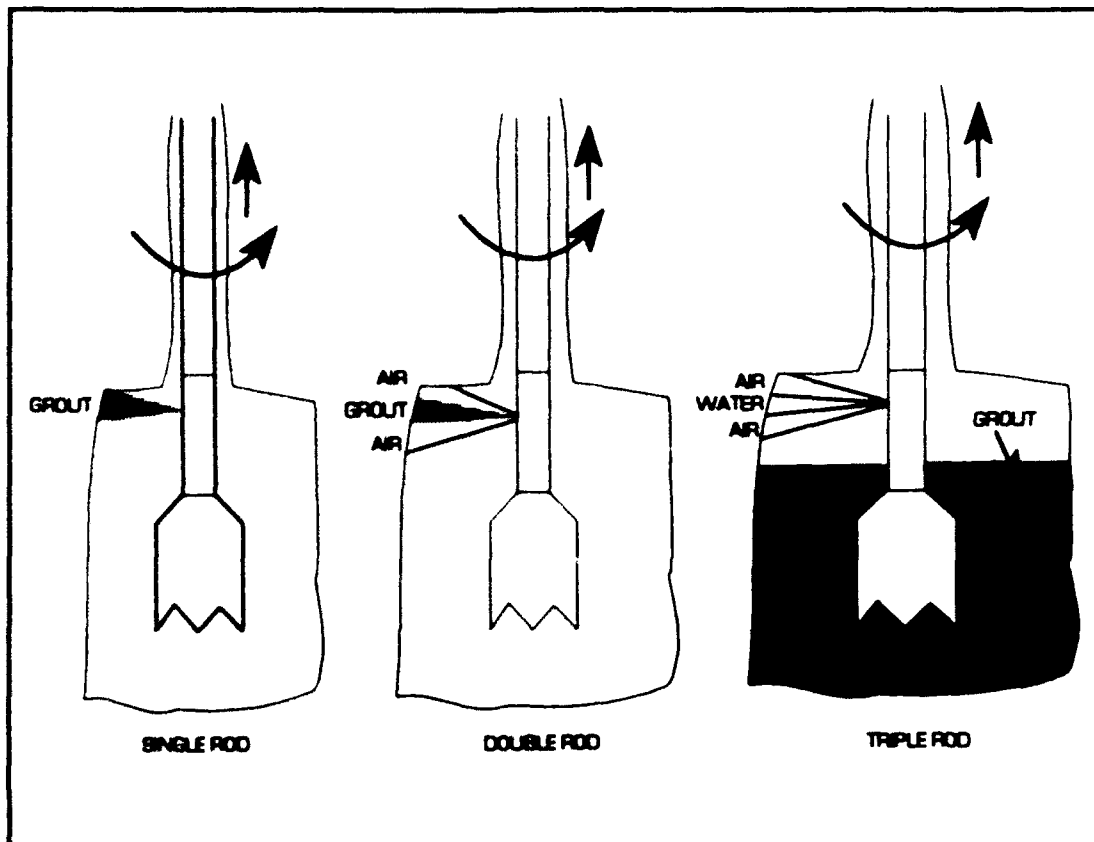
Figure 2-3

The single rod system injects the cement slurry grout under high pressure and velocity, which cause the mixing of the soil-cement matrix, or soilcrete. With the single rod system, the strength and uniformity of the soilcrete is dependent upon the nature and consistency of the in situ soil. With the double rod system, the injected slurry grout is surrounded by a sheath of high pressure air, which allows for a better cutting

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efficiency of the slurry grout, but also produces a soilcrete with a high air content, and a larger permeability.

The third type is the triple rod, which uses a combination of high pressure water and air to cut and lift out the in situ soil, which allows the void that has been cut to be filled with the cement slurry grout. With the triple rod system, the soil can be mixed with the grout, or the soil can be removed and replaced completely with the injected grout. The triple rod also can cut larger holes than the single rod or double rod system, up to 12 inches in diameter.

Jet grouting has many advantages. The different types of jet grouting allow for varying degrees of mixing and replacement of the in situ soil. Jet grouting is not as dependent on the porosity/permeability restrictions that the permeation and displacement grouting methods must overcome. And although jet grouting is more difficult in plastic soils, it can effect soil stabilization over a much wider range of soils, particularly when encountering non-homogenous conditions. Jet grouting provides the most controlled means of grout application, providing columns or panels of specified quality and size at exact locations. Case histories

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performed have produced the following results (Welsh, 1992):

JET GROUTING PRODUCT

Parameter	Granular Soils	Cohesive Soils
Diameters (Feet)	2.5 to 6.0	1.5 to 5.0
Unconfined Compressive Strength (psi)	700 to 1500	150 to 750
Shear Strength (psi)	70	40
Modulus of Deformation (psi)	70,000	15,000
Permeability (cm/sec)	10^{-6} to 10^{-7}	10^{-6} to 10^{-7}

Jet grouting holds great promise in waste site remediation. Construction of a bottom barrier is possible through jet grouting, since testing has shown that jet grouting could develop adequate overlap for effective sealing in compacted sand. However, the grouts were not as effective in silt. This technology has been used for in-situ removal of contaminated soils below structures.

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Jet grouting was used in Germany for a site contaminated with phenols (Mitchell, 1992). After sealing the ground surface, a bore hole was dug, after which a bentonite slurry was used to wash out the contaminated soil, which was contained and collected at the surface. The contaminated material was treated by soil washing and oxidation degradation, and the coarser soil particles that could not be flushed out were adequately clean with the injected air and fluid jets. The cleaned soil was mixed with purified wash water and cement to make the backfill. As the backfill was re-injected into the hole, the contaminated slurry that was pushed out was collected and treated. This process minimized the amount of material that had to be disposed of in a hazardous waste landfill.

While jet grouting holds promise for waste site remediation, it does have some shortcomings. One disadvantage to jet grouting is the drill hole opening is the only exit for the displaced soil cutting and fluids. If care is not taken, this opening can become plugged, causing excessive pressures to hydrofracture the subsurface. Another disadvantage is the large amount of waste that is produced. At contaminated sites, contaminated fluids and soils removed from the bore hole

will have to be treated and disposed of properly (Rumer, 1993).

3.0 GROUTING TYPES

The term grout is used for several different
substances. The term grout is being applied to plastic
mortars, thick or liquid suspensions of cement as well as
other compounds and additives in water, solutions of
chemicals, resins, artificial foams, and also to hot
bitumen and bitumen emulsions. For the purposes of this
paper, the term grout will be used to define suspensions
or solutions that are injected in situ into the porous
media. The term suspensions usually is associated with
cement type mixes, while solutions frequently is the term
used for chemical grouts.

3.1 Grout Suspensions

Grout suspensions, or cement based grouts, can
consist of six materials. These materials include:
cement, bentonite, clay, fillers, additives, and water.
Fillers are used when grouting soil with large voids,
while additives are used to stabilize the grout. Nearly
all suspension grouts are composed of two or more of
these materials. In practice, no uniform system exists
for describing the mixed quantity of each substance.
Many of today's commercially manufactured and prepared
grouts are proprietary, so that the content can sometimes

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only be estimated. To understand how the grout reacts in the ground, it is essential to first understand the materials that compose this substance.

3.1.1 Cement

Often referred to as Portland Cement, cement is often marketed under different types such as high furnace or metallurgical, pozzolanic, and sulfate resistant cement. These types can also be rated by the strength that they achieve over a period of time, and by the heat that they release during setting. Pozzolans, as silicates and aluminosilicates, are not by themselves cementitious, but will react with free lime cement in the presence of water to form a cementitious compound (Littlejohn, 1982). Artificial pozzolans include flyash and ground blast-furnace slag.

Several standards exist that define the properties of the cement. The chemical composition usually consists of a standardized range of SO_3, MgO, $3CaA_2O_3$, of added inerts, fly ash and pozzolans (Nonveiller, 1989). Whereas the standard physical properties include:

- the fineness of the grains

- the unit mass

- the length of time for setting

- volummetric and linear strain after setting

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- the strength after 3, 7, and 28 days.

All of the above physical properties can be measured in the laboratory with standard ASTM tests.

As a result of concern with control of the grouted media's permeability, the one physical property that is the most crucial in selecting the grout is the fineness of the cement grains. One should select a grout with a high fineness content, while the other properties would merely define the cement as a standardized product which is suitable for grouting purposes.

When grouting soils that are less permeable, a special type of cement can be utilized to help penetrate smaller voids. This special cement, called microfine cement, is actually cement that is finely ground. With microfine cement, the penetrability is comparable to that of chemical grouts. For constructing a low permeability bottom barrier, the use of microfine cement will play a key role.

3.1.2 Clay

While the term clay is used in a broad sense, in the grouting practice clay is defined to include soil grains smaller than two micrometers, and a set of specific minerals. The building blocks of the clay minerals are:

-silica tetrahedrons assembled in sheets on a

hexagonal grid in which every three of four oxygen

atoms are assembled around a silicon atom.

-aluminum or magnesium octahedrons coordinated in

sheets with a common oxygen atom or hydroxile

group around the aluminum or magnesium atoms.

These building blocks can be seen in Figure 3-1 in the

schematic of kaolinite and montmorillonite clay
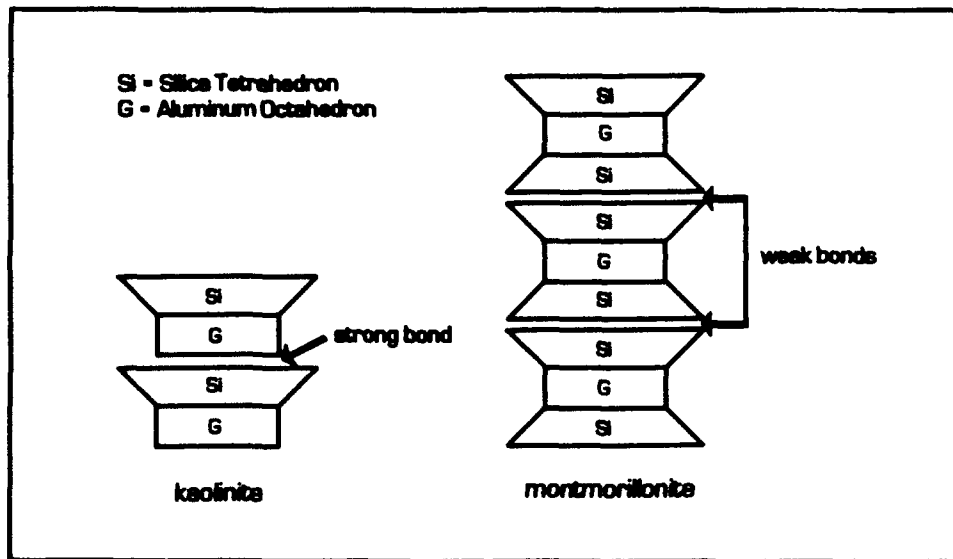
particles.

Figure 3-1

Kaolinite and montmorillonite represent the most

common clay particles in grout suspensions. The

kaolinite mineral consists of one strong bond, that is

strong enough to resist swelling when introduced to

water, and form regular platelets of hexagonal shape with

a length of 1-4 micrometers, and a thickness of 0.05 to 2 micrometers. Kaolinite is widely used as a filler in suspension grouts.

Montmorillonite consists of three blocks in the arrangement shown. The bonds are weak, and can be broken easily by splitting or adsorption of water molecules, which leads to a high swelling potential. Montmorillonite forms minerals with a length of 1-2 micrometers, and a thickness of 10^{-3} to $2x10^{-2}$ micrometers. Montmorillonite is used to stabilize cement suspensions, and is used in drilling muds.

Bentonite is actually a montmorillonite clay that contains small quantities of inert mineral grains (quartz, feldspar, calcite, etc.). Bentonite, as mined, often contains calcium ions that can be readily replaced with sodium ions. The calcium bentonite has plastic/liquid limits of about 30/100%, while the sodium bentonite's limits increase to 50/400% (Nonveiller, 1989). The bentonite is used to stabilize the cement, thus preventing its bleeding, and the sodium bentonite is especially favorable in grout formulation.

3.1.3 Fillers

Often the main purpose of the fillers is to reduce the cost of the grout without significantly reducing its

effectiveness. Sands are the primary fillers, while
clay's role is often thought of as a filler, and to a
lesser extent, pozzolans could also be defined as
fillers. Today, most grout fillers are sand, and are
used to help grout areas where large fissures are to be
injected. Other materials that could be used for fillers
in grouting large fissures include: dust, wood shavings,
strips of cellophane, polyvinyl or polyester.

3.1.4 Additives

Although only relatively weak forces are acting upon
the planes between the sheets of clay minerals, an
unbalanced electrical charge still exists. This charge
attracts and binds adjacent single crystals into large
agglomerations (flakes), which affect the physical
properties of the suspension. The changed properties
could include less suspension stability and more
viscosity, which are not ideal. To prevent the
flocculation of clay particles in a suspension, small
quantities of ions are added to neutralize the unbalanced
charges. This allows the individual clay particles to
repel each other and allows the individual size of the
suspended particles to remain seperate rather than to
flocculate into aggregates of particles. The additive is
called a plastifier, and is most commonly a sodium

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carbonate or bicarbonate.

One can improve the pumpability of a thick cement
suspension by adding commercially available air
entraining agents. Accelerators can also be added to the
grout to improve early grout strength and to speed up the
set time. However, accelerators usually reduce the final
strength of the grout mixture.

3.2 Solution Grouts

Solution grouts, or chemical grouts, are injected
into the ground, and form gels that fill the soil voids
and pores. This reaction lowers the soil permeability
and can also increase the soil strength. Almost 90% of
the chemical grouts used are derived from sodium silicate
formulations. However, several other type of chemical
grouts exist and include:

        a. Acrylics

        b. Lignosulfites-Lignosulfonates

        c. Phenoplasts

        d. Aminoplasts

However, in the last decade, the use of chemical grouts
has declined, primarily due to toxicity concerns. The
use of chemical grouts can adversely affect the
environment and the crews that come into contact with it.
Some chemical grouts may be toxic, neurotoxic,

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carcinogenic, or irritating to exposed skin. Leaching of grout could lead to damage of the ground water supply and the environment.

Earlier use of chemical solutions was necessary as suspension grouts could not permeate into soil as well as chemical solutions. With the use of microfine cement, suspensions are now as capable of grouting finer soils as the chemical grouts (Karol, 1990). Hakansson (1992) reports that microcement is becoming increasingly popular in replacement of chemical grouts, since the particles are much smaller and can therefore penetrate into narrower voids. Because fine particulate grouts generally have equal penetrability and fewer environmental problems, the author will not discuss chemical grouts in any further detail. The results of testing chemical grouts in an aggressive environment will be discussed in Section 3.4.

3.3 Grout Characteristics

The grout is expected to display certain acceptable characteristics or properties. The most important grout properties include:

      a.   stability of grout suspensions

      b.   penetrability/dynamic viscosity

      c.   strength of the injected grout

d. permeability of injected grouts

e. resistance of injected grout to erosion

and chemical deterioration

When selecting a grout, one first selects the anticipated components. These materials are mixed in different compositions, which are then laboratory tested to find an optimum mixture. The final composition is optimized based upon the properties needed (Nonveiller, 1989). For example, the mixture of components could vastly differ from a grout used in stabilizing a soil versus a grout used in lowering the permeability of that soil.

3.3.1 Stability of Grout Suspensions

Stability of the grout suspension requires that the suspended particles do not settle out during the grouting process. Stable suspensions are those that do not settle at all after at least 24 hours. Basically, the smaller the particles in the suspension, the slower they settle. Stoke's Law states that the larger the particle size, the quicker a particle will settle due to gravitational forces. However, the smaller particles will settle even slower than predicted through Stoke's Law because of the electrochemical forces that are acting on the colloidal particles that are less than one micrometer in size (Nonveiller, 1989). Laboratory test ng for stability is

a simple but important process.

3.3.2 Penetrability/Dynamic Viscosity

One of the grout's most important characteristics is it's penetrability, or ability to permeate the media that it is being injected into. Penetrability can be indirectly measured through a grout's dynamic viscosity. The dynamic viscosity is proportional to the ability of a fluid to produce shear during flow.

Shear strength is the ability of a material to reach static equilibrium rather than deform continuously. However, fluids do not possess shear strength, but do offer a resistance to deformation through internal molecular friction. As such, fluids will continue to deform indefinitely under the influence of a shearing force. Viscosity is actually a measure of the internal friction mobilized against the shearing forces (Karol, 1990).

The yield stress of the grout has been considered as the material property that represents the transition between solid-like and fluid-like behavior. The grout behaves as a weak solid when below its yield stress, and behaves like a Bingham fluid above this stress. However, one must consider that the grout is not just a suspension, but is also subject to a chemical reaction

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during the hydration process, that can affect its behavior. The most important factors that influence the flow characteristic are (Hakansson et al, 1992):

a. water/cement (w/c) ratio

b. specific surface (fineness)

c. cement type (mineral composition)

d. cement hydration (i.e. time dependency)

e. mixing time and intensity

f. temperature

Several different laboratory methods exist for measuring the viscosity of the grout. Shown in Figure 3-2 are the relative penetrabilities of several grouts (Karol, 1990).
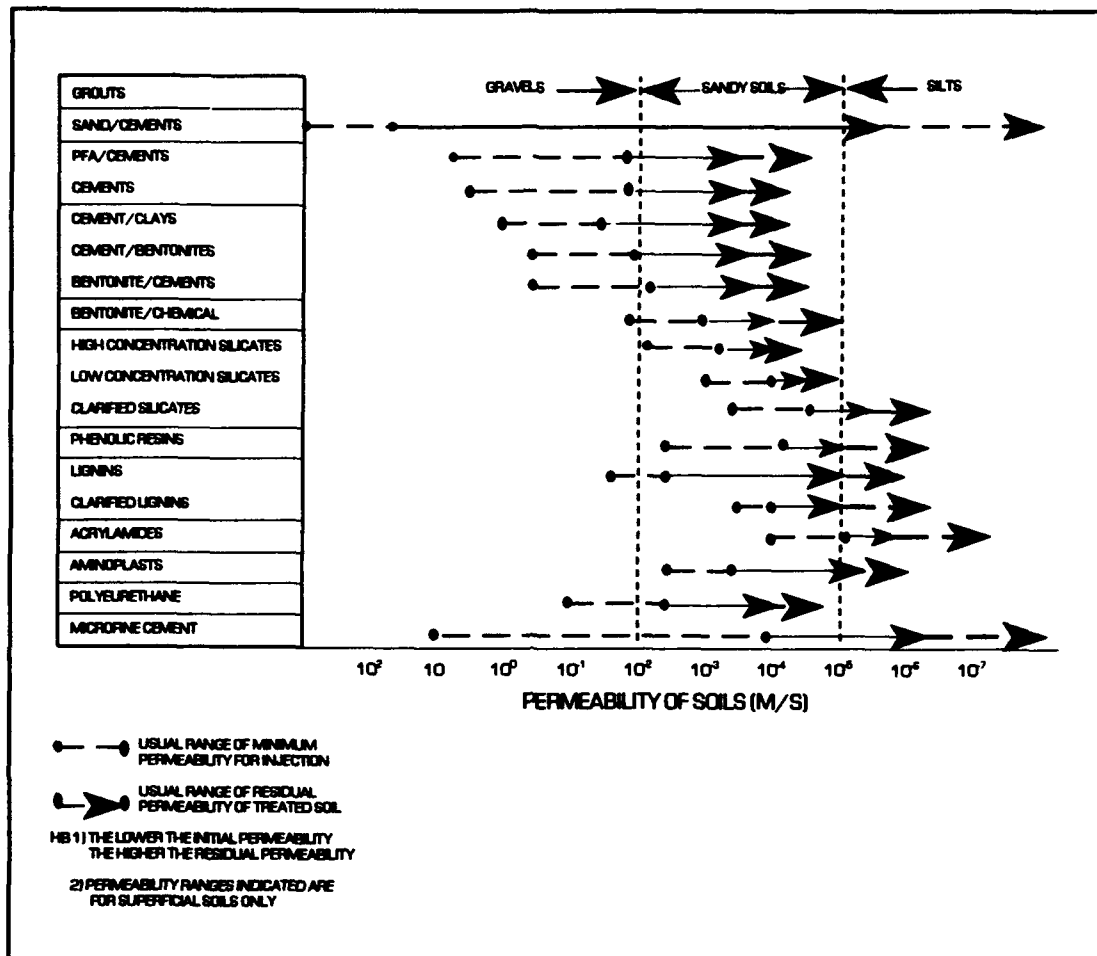
Figure 3-2

3.3.3 Strength of the Injected Grout

Several factors affect the strength of the injected grout. The most important variables are: the water content of the grout, the pore space of the set grout, and the type of cement and additives (Littlejohn, 1982).

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Nearly all cement grouts experience strength gains over a period of time, up to a year, before leveling off.

While strength is not the essential property in grouting waste sites, the grout must possess enough strength to prevent the grouted media from fracturing. In estimating the strength of the injected grout, it is essential to test the grouted media at the water content that is expected in situ. Often the grouted media is tested after oven or air drying has occurred. When water held by the grout mixture is lost through desiccation, the grout mix shrinks. This shrinkage causes the soil grains to narrow and set up forces between them that are analogous to capillary tensile forces, except much stronger. It is possible for the dry sample to show strengths up to 10 times the in situ strength (Karol, 1990).

The strength of the injected soil depends not only on the grout, but on several soil properties which include:

- soil density
- average grain size
- grain size distribution

Often, strength increases with increasing density and with decreasing grain size, and well-graded soils give

higher strengths than poorly graded soils. This often leads to the anticipated strength of the injected soil given as a range of values rather than a specific number (Karol, 1990).

3.3.4 Permeability of Injected Grouts

One of the most important factors in selection of a grout is the final permeability of the injected grout. Ideally, the injected grout should have a permeability of 10^{-7} cm/sec or less. This value is chosen because it is the U.S. Environmental Protection Agency's standard for containment of hazardous waste. Measuring permeability as low as 10^{-7} cm/sec can be difficult and time consuming. Often, it is best to do a field measurement of the injected grout's permeability, as laboratory testing does not take into account irregularities experienced in the field.

Permeability can be affected by secondary features, curing time, and other factors. In fact, one paper is dedicated to the differences in permeability based upon the orientation of the grouted material when it was cured (Krizek et al., 1992). In this test, plastic laboratory tubes were injected with grout while aligned either vertically and horizontally along the longitudinal axis, and then allowed to cure. The permeability of the

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vertically cured specimens of cement-grouted sand were orders of magnitude less permeable than horizontally cured specimens. It has also been shown that increasing the solids content in the grout will decrease the permeability (DeGroot, 1993). This is especially useful since construction of an impermeable bottom barrier will more likely include horizontal curing. However, this illustrates how lab testing often does not represent field results.

Section 3.4 is dedicated to determining the permeability against aggressive materials expected at the site. It is essential to understand that the permeability of the injected grout could dramatically change as pore volumes of water and/or chemicals leach through the grout.

3.3.5 Resistance of Injected Grouts to Erosion and Chemical Deterioration

Injected grout strength and permeability can worsen over time due to leaching of grout particles out of the injected soil mass. Chemical deterioration of grouts can occur if the grouts react with soil or groundwater to form soluble reaction products. Further, if the grout itself is soluble in groundwater, or if the reaction

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products which form the grout are inherently unstable, chemical deterioration will occur (Karol, 1990). It is also possible that the slow permeation of water through the grout will substantially deteriorate the grout, reducing its efficiency. Water not penetrating completely through filled fissures may more intensively deteriorate the grout and cause deterioration of the grouted works in a much shorter time (Nonveiller, 1989). Some aggressive materials to grout include:

a. sulfates, which deteriorate calcium compounds in the cement

b. carbon dioxide, which dissolves free lime of the cement or calcite minerals contained in the sand

c. humous acids

d. very soft water, which dissolves calcite salts

3.3.6 Other Factors

The previously discussed factors include the major properties of grout that one would review before selecting a grout. Other factors that should be considered include: the thixotropy of the injected grout, the set up time, costs, ease of production,

solubility in water, temperature effects, and toxicity (environmental effects). When selecting the proper grout, one should also consider the experience of local contractors in applying grouts, and their success with various grouts. Numerous factors need to be examined in the selection and testing of the grout.

3.4 Testing Procedures of Selected Grouts

Jefferis (1992) detailed a method to insure that laboratory testing properly shows the effect of contaminants leaching through a grout. Jefferis emphasized that the two most important factors in laboratory testing are the number of pore volumes of flow and the amount of time needed. When determining what contaminants at the site may cause the most damage to the injected grout, it is important to realize that contaminants most damaging to the grout may be quite different from those that are damaging to the environment. In fact, on occasion, it may be appropriate to design a grout to react with and retain/remove specific contaminants as a sacrificial system which must be replaced if the absorption/reaction capacity is depleted before all of the contaminant is removed. (Jefferis, 1992)

Essentially, the only way to assess the grout-

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chemical compatibility is to carry out the necessary
laboratory testing, which can be extremely time
consuming. Basically, three testing procedures are used
for testing the grout-contaminant compatibility. They
include:

- mixing the grout with the appropriate volume
  of the contaminant solution and analyzing
  the reaction products (i.e. impact of
  contaminated water on grout properties)
- immersing the grout specimens in the
  contaminant
- permeating the grout with contaminant

After reviewing several tests, Jefferis came to following
conclusions:

a. Laboratory test procedures are not yet
   satisfactory for the assessment of field
   durability. More complex models are needed
   that include multiple permeabilities and
   allowing for diffusion as well as
   permeation.

b. The reacted permeability cannot be
   predicted from the early age data. In
   fact, in the first few weeks, permeability

of the sample decreased, after which it began to increase, not leveling off until several months.

c. When assessing the effects of reactive chemicals, the major source of damage may be simple dissolution of the grout material without any specific chemical reaction.

d. Often a significant number of pore volumes of flow are needed to determine grout-contaminant interaction.

In selecting the grout, extensive tests are required to ensure that the grout that has been selected is optimum for the site and conditions. As explained, this selection process can be lengthy and costly, but the ramifications of picking an improper grout or not fully realizing its limitations can have a much more costly impact.

3.5 Case Histories of Grouting in Hazardous Environment

While grout has been applied to numerous sites that experience aggressive contaminants, not much information has been published on the results. One problem that is encountered is the composition of commercial grouts is usually proprietary and is not disclosed. Another

problem is that not much public-domain research has been performed to study the effects of chemicals on commercial grouts. When selecting a grout for testing, one would best first contact the manufacturers of the grout, and ask for their recommendation. This often will at least provide a starting point for laboratory testing.

3.5.1 Slurry Wall Case Studies

Some research and field results have been published on the effect of contaminants on slurry wall performance. Although there are differences and similarities between slurry walls and grouts, the author believes that comparisons and effects on grout components can be extrapolated based on these experiences.

Walter E. Grube (1992) of the U.S. EPA has published several experiences based on slurry wall design and construction. Grube notes that EPA approval of a slurry wall requires that the permeability of that wall does not increase. In sodium-bentonite slurry walls, the bentonite can lose its cation (Na) and its corresponding swelling capacity in the presence of salt water containing cations such as calcium, magnesium, iron and aluminum. Further, if the slurry wall intersects immiscible pools of groundwater contaminants, the potential for barrier degradation is high, and will not

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be reflected in contaminated groundwater tests. Finally, the use of adsorbing or reactive material to capture or neutralize contaminants is still too new of a technology, and needs to undergo further testing and agency review before it will be a uniformly accepted technique.

Research has shown that the type of bentonite used in slurry wall construction can have a large impact on its interaction with contaminants. Tests have shown that the permeability of soil/sodium bentonite mixtures often dramatically increase when exposed to organic waste chemicals. When the same permeant is applied to a calcium bentonite mixture, the hydraulic conductivity can actually decrease. Sodium bentonite mixtures realize their low hydraulic conductivity from an abundance of monovalent ions and will experience a higher hydraulic conductivity when these ions are replaced by higher valence ions. Finally, the greater resistance of calcium bentonite to organic chemicals may be partially due to the fact that its water absorption capacity is essentially constant in the entire pH range (Khera et al., 1992).

Rumer et. al. (1993) reported several conclusions based upon previous publications on soil-bentonite compatibility which include:

a. The soil-bentonite mixture permeated with
    concentrated organic contaminants will
    likely experience a larger increase of
    hydraulic conductivity than when permeated
    with water.

b. Increases in permeability due to permeation
    with concentrated organic contaminants or
    with inorganically contaminants are
    limited. In other words, the permeability
    initially increases, and then levels off to
    a new equilibrium value.

c. Increase of non-colloidal material in the
    mixture will tend to reduce the effect of
    the organic liquid.

d. Permeating the mixture with strong acids or
    bases could cause dissolution of the soil
    skeleton, increasing the hydraulic
    conductivity.

e. Soils, when permeated by acids or bases,
    inherently have a buffering capacity that
    may delay the hydraulic conductivity
    increase.

3.5.2 Grout Case Studies

Grouts differ from slurry walls in the fact that

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solution grouts are based upon cement as the primary component, while many slurry walls utilize bentonite as its principle component. Often the grout mixture has a profound impact on the effect of the permeant.

Several chemicals are inherently destructive to portland cements grouts. These chemicals include carbon dioxide, sulfates, humous acids, and very soft water. Sulfates attack the calcium compounds, which can be prevented by using sulfate resistant cement. Carbon dioxide, which dissolves the free lime, can be countered by adding microsilica to the grout mix. Finally, acidic soils can adversely affect the chemical reaction that causes the concrete grout to set up (Rumer et al., 1993).

John Siwula and Raymond Krizek (1992) experimented by using four different grouts in Ottawa 20-30 sand. The chemical grouts were permeated with both high and low pH solutions, and a single concrete grout was subjected to high and low levels of sulfate solution. The grouts used included two silicate based grouts, one microfine cement grout, and one acrylate grout. The acrylate grout performed the best: no measurable flow was attained through any of the samples. Both silicate grouts performed acceptably, although they gave permeabilities of less the 10^{-7} cm/sec in a high pH environment.

The microfine grout performed poorly, achieving a permeability of about 10^{-4} cm/sec. However, the sulfate level appeared to have little impact on the final permeability. The samples were tested with little cure time; in fact, the longest curing time allowed was seven days. The relatively high permeability was not caused by the grout matrix, but rather was due to the settling of cement particles that formed preferential flow paths (Siwula et al., 1992). It appears that no attempt was made by the researchers to stabilize the grout solution and to perform the experiment again. The author is confident that the grout solution would have performed satisfactorily in the right mixture and injection procedure.

In an industrial landfill in upstate New York, grouting was used to construct a grout curtain to help improve the hydraulic conditions and the pump-and-treat remediation effort (Weaver, 1992). Nine different grout brands were tested and evaluated. The properties of interest to the engineers were viscosity, bleed, permeability, and compatibility with the chemical environment. The tests showed that various formulations of type 1 portland cement and class F fly ash, type V portland cement, and microfine cement had acceptable

properties and were contaminant compatible. The final grout mix was tuned during the injection, and was based upon the volume of grout injected and the rate of grout take. To date, no deterioration of the grout curtain has been observed.

Jet grouting was used in Northern New Jersey to create a small horizontal bottom barrier to prevent future contaminate migration in an underlying aquifer (Gazaway, 1992). The grout mixture had also been used to patch a slurry wall in Northern Michigan. The grout mixture used was based upon a bench scale study performed for these sites. The mix used consisted of approximately 17% (by weight of the slurry) type 1 portland cement, and 9% sodium bentonite. Samples were removed from the ground and tested. All samples exhibited permeabilities less than 10^{-7} cm/sec, with the average at 2.9×10^{-8} cm/sec. These permeabilities are actually lower than expected, but the researchers hypothesized that the finer fraction of the soils at the sites, coupled with homogeneity of the soil/grout mixture, may have contributed to the achievement of these values.

Past successes help in formulating the best grout alternatives when approaching a project. However, past successes do not alleviate the requirement of testing

site specific soil and contaminants for their impact on the construction of the bottom hydraulic barrier. Only with thorough laboratory tests should the designer feel comfortable in approving the final grout mixture.

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4.0 BOTTTOM BARRIER

CONSTRUCTION TECHNIQUES

Even though surface and vertical barrier systems have been used for numerous years in attempting to prevent contamination migration, bottom barrier schemes have not been attempted. Jet grouting appears to be a viable technology which may produce economical and predictable bottom barriers. In construction of bottom barriers, the United States is not leading the race for new techniques; it appears Germany is on the forefront. Germany has over 50,000 known hazardous waste sites and a strong mining industry. Thus, the strong need and essential tools and techniques are available and closely concentrated for this effort. However, only a few attempts have been described in the literature, but many ideas are feasible in construction of a bottom barrier.

4.1 Recent Attempts and Published Techniques.

4.1.1 Northern New Jersey

Gazaway and Jasperse (1992) write of a recent attempt in Northern New Jersey to construct a bottom barrier. A storage tank had been removed from this site,

and the excavation had been backfilled with silty sand fill. Later, chlorinated hydrocarbon contaminants began to migrate into the clean backfill from adjacent soil, and began to migrate down through the porous backfill towards the groundwater. Block stabilization was chosen as the remediation technique to prevent the downward flow of contaminants into the underlying aquifer.

The size of the site measured only twenty feet by twelve feet, to a depth of ten feet. In construction of the barrier, a primary grid pattern with a spacing of five feet was chosen and grouted. Then, an overlapping grid of the same size was drilled, providing equal spacing between the previous drilling. The site was grouted according to the following parameters:

-Jet Nozzle Range: 5.5 to 6.8 feet

-Grout Pressure: 6,000 psi

-Rotation Rate: 1 rpm

-Lift Rate: 1 foot per minute

The grout was a cement/bentonite mix that was discussed in Chapter 3. The grout's effectiveness was verified through testing of undisturbed samples, and consistently yielded permeabilities less the 1×10^{-7} cm/sec, which

were consistent with results from the bench test. The low permeabilities were hypothesized to have been the result of the presence of fines in the soils at this site (Gazaway et al., 1992).

The results from this test are encouraging but cannot be applied to all situations. In the New Jersey site, drilling occurred at the surface since the source of contamination was already removed. At most waste remediation sites, surface drilling is not a viable option. The site also experienced problems with the soil heaving close to the surface, which is highly undesirable, since this will often lead to large secondary porosity features.

4.1.2 The Zublin System

While the site in New Jersey represented a small scale approach to construction of a bottom barrier, two approaches in Germany are being investigated with a much larger perspective. The depth of mining experience and capabilities combined with the serious environmental problems in Germany have led two German firms to develop similar techniques in construction of a bottom barrier.

Rumer and Ryan (1993) write of a system proposed by H.L. Jessberger. The system would result in a containment structure similar to a bathtub. The

construction is started with excavating two parallel open
trenches on opposite sides of the site, as shown in
Figure 4-1. From these trenches, large steel pipes, with
a nominal diameter of 7.5 to 9 feet, are bored and pushed
into the site. The pipes are spaced at 20-30 foot
intervals, and can be pushed up to 450 feet. The layout
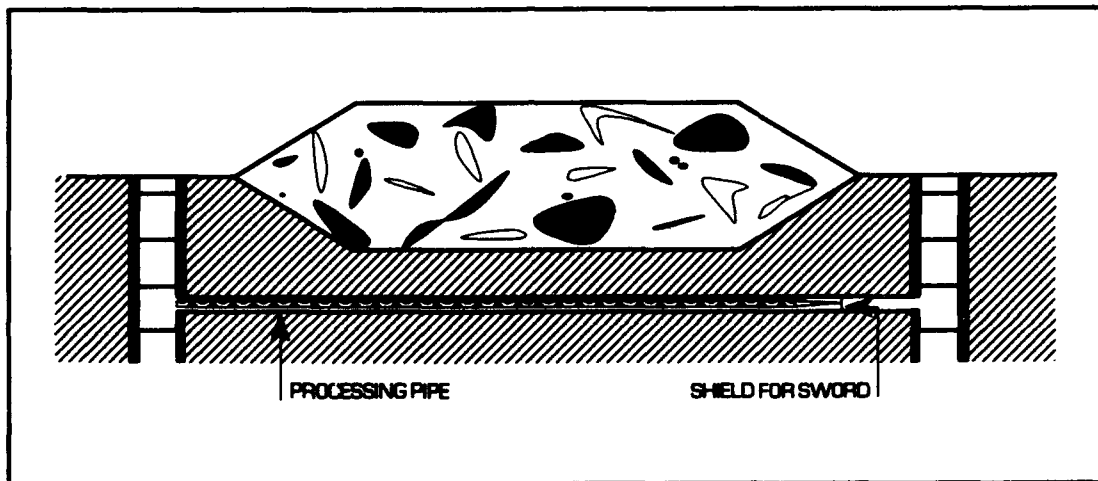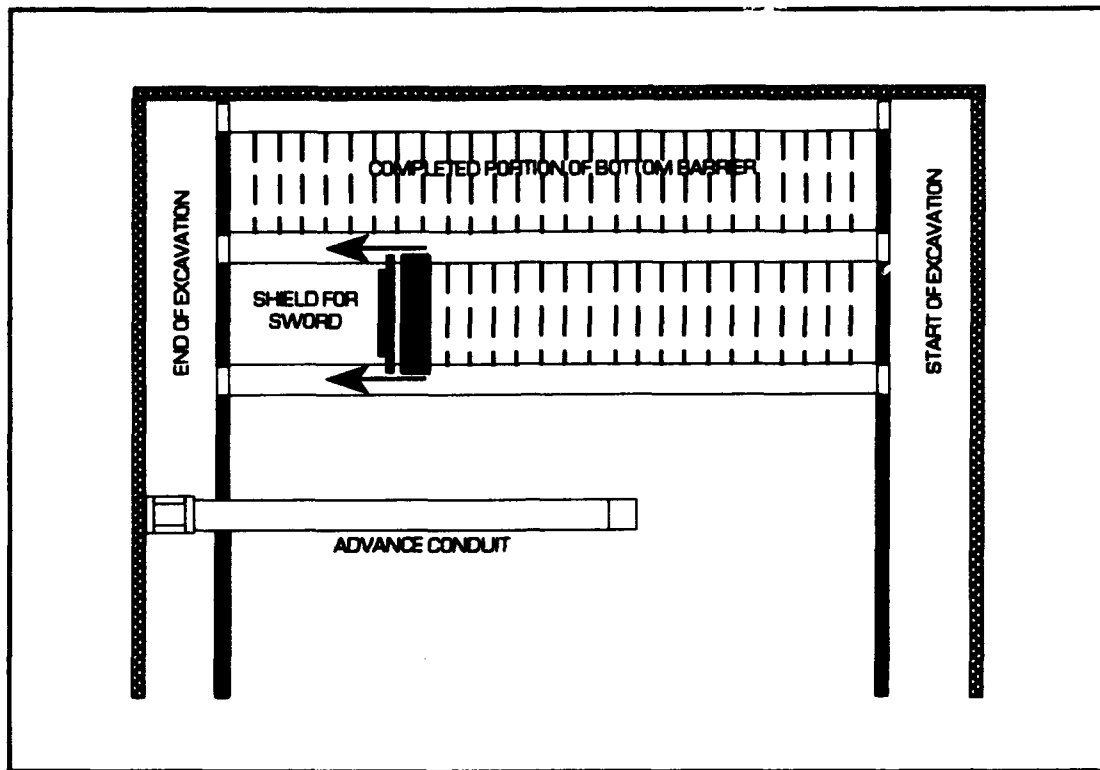is shown is figure 4-2.

Figure 4-1

Figure 4-2

The tubes must be aligned very carefully since a special excavator, called the "sword," travels between the pipes, using them as a guide. The sword simultaneously jets and cuts the soil ahead, prevents the tunnel from collapsing, and assists in the placement of the liner system between the pipes. A liner system consisting of a high-density polyethylene membrane is pulled between the pipes, and quick-setting grout is injected on both sides of the membrane. Seams between the strips of HDPE membrane are thermally sealed.

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The parallel pipes form the heart of the Zublin system, and are useful for a number of functions. The pipes are large enough to accommodate workers and equipment, and can be used to verify that the system is working properly. When repairs are necessary, the pipes would provide access to the area. Keying the vertical barriers into the bottom barrier can be accomplished by splicing the two components.

The Zublin system has not been built, and is obviously a very expensive alternative in containment, and would require a high degree of expertise during construction. The system would allow for inspection, monitoring, and repairs.

4.1.3 German Base Sealing System

Dr. Thomas Hollenberg and Dr. Klaus Weibezahn (1993) have been devising a system for two companies in Germany. In many respects, the system parallels the Zublin System. The excavation of the site would be accomplished via the cut-and-cover mining method, where the excavated area is backfilled straight away with the exception of an access tunnel to the face. Hollenberg et al. (1993) details out the requirements of the system:

-the access tunnels and the working chambers

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must be protected against contaminated water
and toxic gases.

-the system must be able to construct the
sealing below the groundwater table.

-A minimum work space is needed for
construction of the sealing, which will
determine the cross section of the machinery.

-All of the overburden must be carried by the
heading system.

-Soil movements must be minimized to prevent
new contaminants paths from opening.

-As the sealing is produced and put into
place, a system to join adjacent strips to
form a homogenous seal must be developed.
Precision cutting and steering are needed to
ensure this linkage.

-The logistics system must provide means to
transport the contaminated material to the
surface for treatment, and be able to provide
the heading system with the material for the
mineral sealing, foil, backfill, and cooling
water, in addition to ventilation air.

-Safety systems must be installed to warn of
toxic fumes or explosive gases.

-The system must allow for continuous monitoring after the completion of construction.

The heading system is the heart of the installation system. The heading system consists of:

A. A blade shield, including a trailer blade shield with working chamber
B. A cutting system
C. A pipe jacking system

Numerous size blade shields are available, and need no abutment while driving a heading. The blade shield allows for virtually vibration-free heading without causing any soil movements above. The machine is capable of cutting through hard rock formations and non-cohesive soils, clays, and marls. The working chambers in the heading system, as well as the cutting machine, are separated through air locks. This enables the machine to work under compressed air, preventing water and gases from entering the heading equipment (Hollenberg et al., 1993).

Two jacked pipes serve as the supply and discharge

pipes for the heading system. Fresh water, energy, mineral sealing material, cooling water, foil coils, and backfill are all transported through these pipes. The pipes also serve as ventilation and personal access. The tunnels are constructed of 9 feet long steel reinforced concrete elements.

The mineral seal that is placed behind the cut is 4.6 feet thick, and consists of an HDPE sheet, plastic foil, geotextile, and drainage gravel. The sealing has six layers that are pressed into place in the heading system. The heading system also contains a foil coil that can be directionally steered and controlled. The coil is steered to overlap the foil from the preceding strip. The foil seams are welded together with a portable extrusion welding machine that has been modified for underground working.

Once the seal is placed, the remaining space in the excavation is filled with backfill that has been grouted. The system also allows for contaminated soils to be transported directly to the surface after they have been excavated. As with the Zublin System, this technique would be extremely costly, but does have great advantages. This system is not as serviceable after construction, but would be superior to grouting a bottom

barrier in place.

4.2 Possible Techniques for Bottom Barriers

While the author believes that the Zublin System and
the German base sealing system show great promise, their
cost will be extremely prohibitive to most sites
considering this technology. However, other techniques
are available that could be used and that might be
economically feasible.

4.2.1 Jet Grouting

Jet grouting has been used to construct bottom
barriers. In fact, jet grouting can be performed using
horizontal, vertical, or directional drilling. Rumer et
al. (1993) proposed using jet grouting to form a bottom
barrier by slant drilling and injection, as s⸲wn in
Figure 4-3.

WASTE

GROUTED
PLANE

CROSS SECTION

SLANTED
GROUT
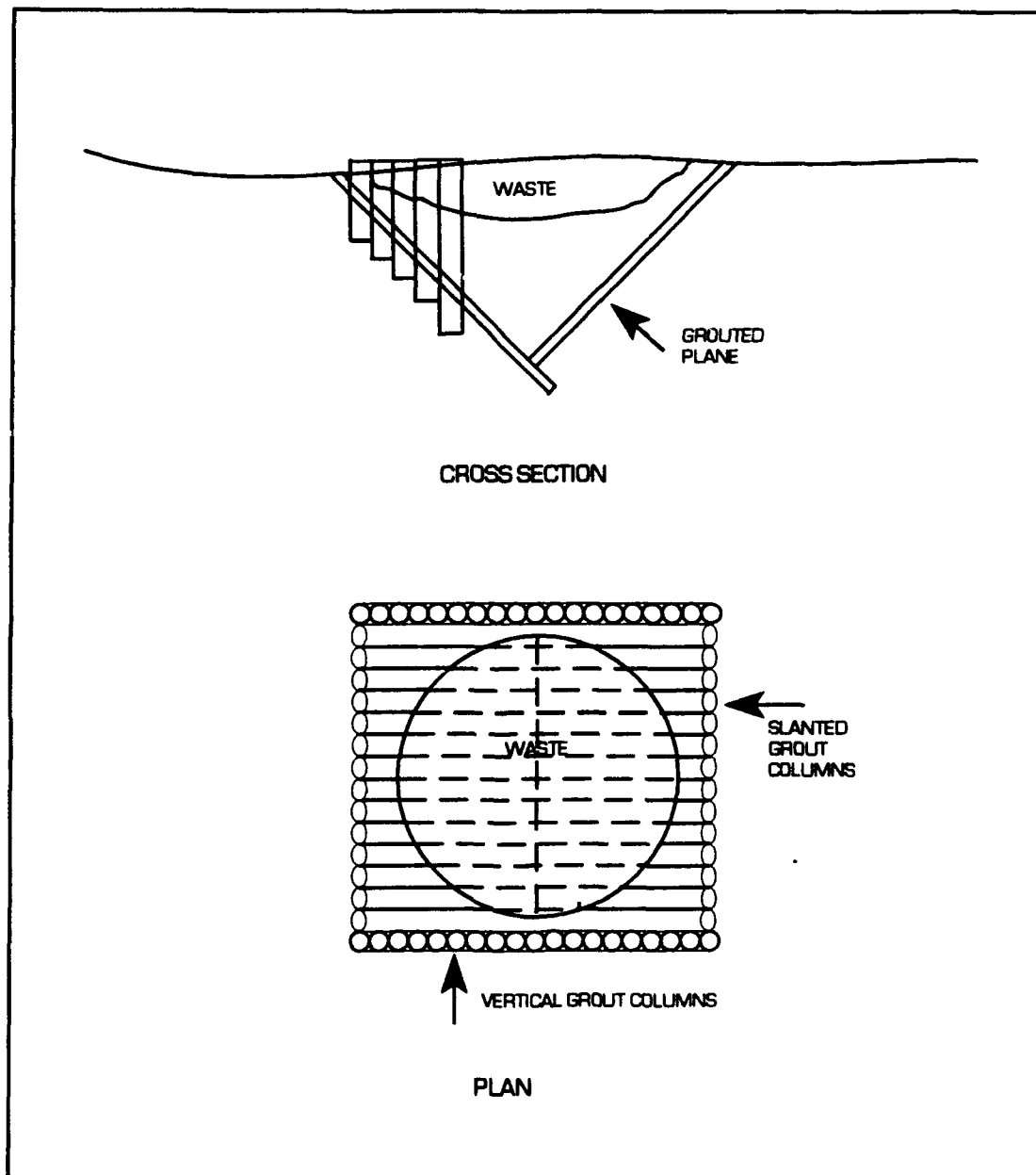COLUMNS

WASTE

VERTICAL GROUT COLUMNS

PLAN

Figure 4-3

A bottom barrier could be constructed using

horizontal drilling, but would be limited to a depth of

50 feet, due to lack of drilling accuracy (Rumer et al., 1993). One problem associated with horizontal jet grouting is the gravitational settling of the grout fines. However, new technologies are coming on line which can make the construction of a thin slab-shaped grout barrier a reality.

Use of a column overlap in jet grouting is often proposed to eliminate discontinuities. Mitchell et al. (1992) believed that this technique could allow for complete isolation of the contaminated area. Jet grouting can develop adequate overlap for effective sealing in compacted sand. In silts and fine grained soils, the cavity could be irregular, and the overlap may not be adequate to provide an effective seal. Use of a down hole sensor is necessary to determine the size of the cavity and for evaluation of the column overlap (Mitchell et al., 1992).

More often though, in the future, jet grouting will be used to construct a bottom barrier. However, it will be supported with other technologies.

4.2.2 Microtunneling

There is no doubt that microtunneling applications will continue to grow. The author foresees the use of microtunneling in conjunction with jet grouting. Rumer

et al. (1993) proposed the system seen in Figure 4-4.
This system involves jacking a perforated pipe, then
using an injection rod to penetrate out of the pipe, and
inject grout into the surrounding soil.
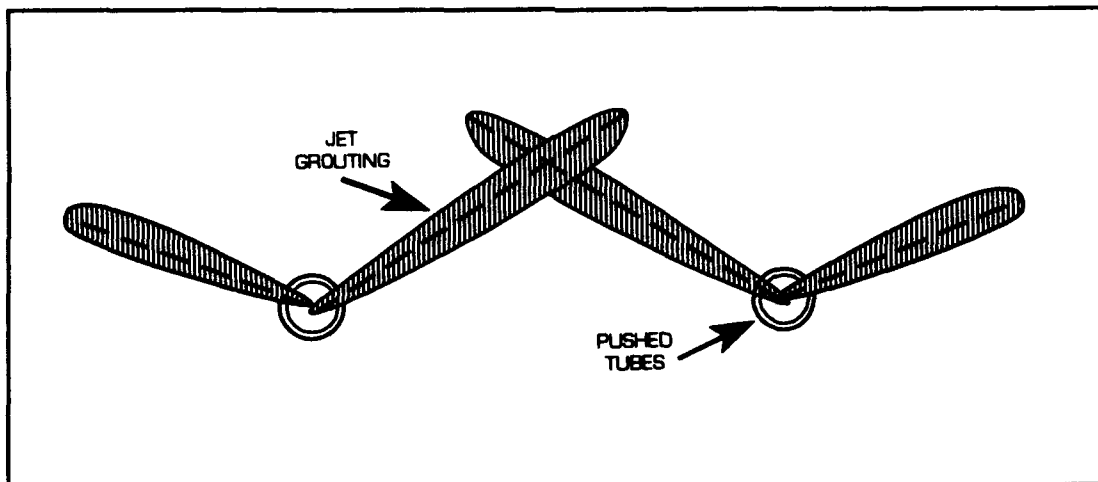

JET
GROUTING

PUSHED
TUBES

Figure 4-4

Rumer et al. (1993) also proposed jacking rectangular
tubes in place, and grouting between them. Although
rectangular tubes are shaped more favorably for this type
of application, their irregular shape will lead to
problems with jacking stress and in situ stress
distribution.

A more suitable technology would involve jacking
large diameter perforated pipes, as close as possible to
each other. Then, jet grouting would be accomplished by
using both the perforated holes first, and horizontal
drilling second. This overcoverage should fill most

drainage paths. A second possibility would involve the same situation, except another redundancy is built in by constructing an overlapping jet grout barrier above the pushed pipes, as shown in Figure 4-5.
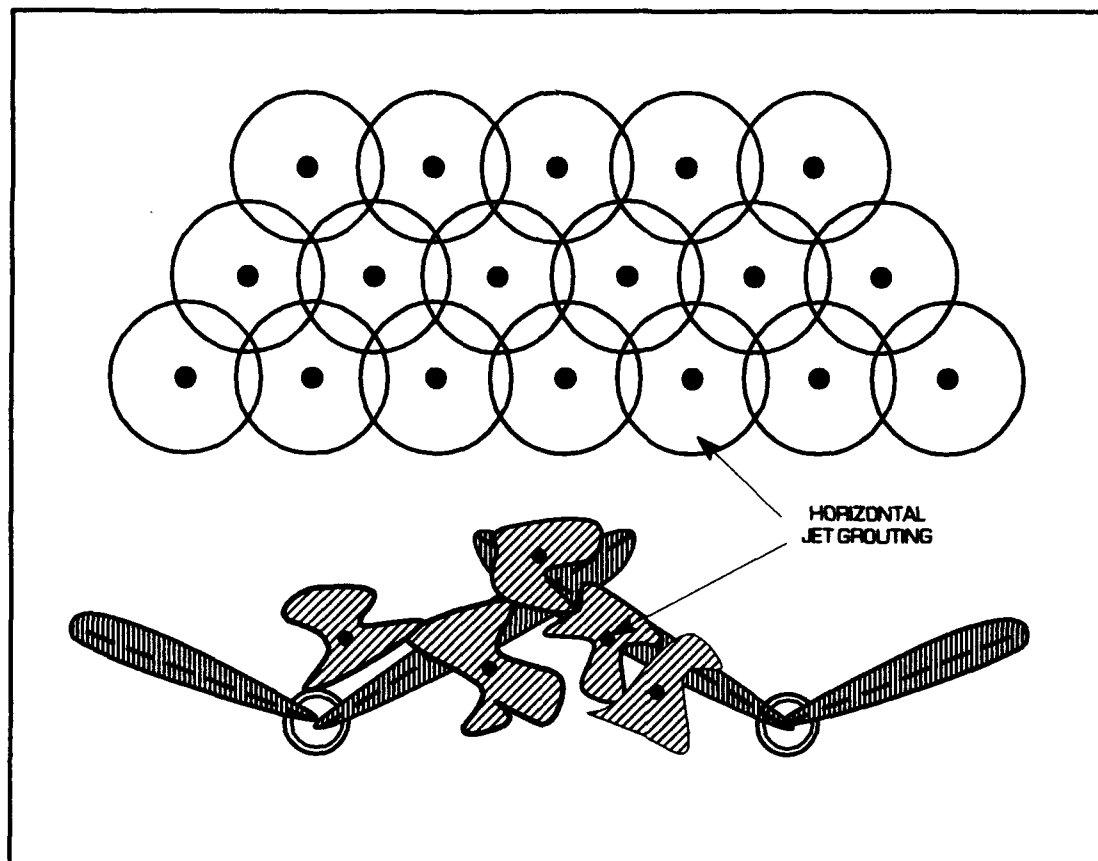

HORIZONTAL
JET GROUTING

Figure 4-5

4.3 Conclusions

While many of the proposed techniques could work, they range in size and complexity from overly cheap and simple to extremely expensive and complicated. At sites where severe risks to public health exists, none of these

simple approaches are recommended, except as stop-gap measures. However, at sites were the risks are low, and one would like to slow the spread of contamination, then this would be an ideal site to experiment with these techniques. Containment of the site may also assist in other remediation techniques such as in situ bio-remediation, bio-venting, soil vapor extraction, or hot air injection.

One important fundamental must not be neglected when installing a bottom barrier, which is to control the head and drainage of the site. Sloping the bottom barrier to an installed leachate collection system will greatly reduce the amount of contaminants that permeate through the "impermeable" barrier. If the barrier is allowed to accumulate a significant head of contaminated water, it is only a matter of time until that leachate finds a path to permeate through. Accepting the EPA limit of leachate head (12 inches) inside of a landfill would be a defendable approach.

When choosing to construct a bottom barrier, one must not forget that the containment will not last indefinitely. Therefore, the containment should be a part of the treatment and remediation effort, not necessarily the only solution.

5.0 CONCLUSIONS

Use of a bottom barrier is only part of a more general containment strategy. Prior to selection and installation of a bottom barrier, a through site assessment must be performed. The site assessment will help to show avenues of preferred drainage and seepage. In addition, the site assessment will impact the type and materials used for the bottom barrier. A cost analysis may show that keying into a deep naturally occurring hydraulic barrier may be more reliable and cost efficient that constructing a man-made barrier.

When constructing the bottom barrier, hydraulic or active control measures, such as extraction and injection wells, are often needed in conjunction with the containment structure to create inward hydraulic gradients that will further minimize the transport of the contaminants out of the structure. In addition, these measures must include a positive means to keep the hydraulic head low on the bottom barrier. After choosing the optimum boring technique, the grout that will be used should be subjected to prolonged permeation from numerous pore volumes of the liquid to be contained prior to

accepting the mixture at the site. In addition, the soil chemistry should also be examined for its compatibility with the grout.

Jet grouting appears to have substantial promise for constructing bottom barriers. This type of grouting is easily performed without significant disturbance to the site, and can be performed through different forms of boring and microtunneling. Large scale tests must still be performed in order to provide reasonable guidance and procedures for future applications. The Zublin System and the German bottom sealing method have not been tried, but these systems hold promise. However, extremely high construction costs would prohibit their use except for only the worst and most troublesome contaminated sites.

The largest problem in constructing the bottom barrier is ensuring that no large preferential drainage paths remain from grouts failing to reach all parts of the area that is to be th   oor structure. In situ confirmation of the construction is nearly impossible, and the only method presently available for ensuring that the containment structure is working is through borings and groundwater samplings outside of the containment structure. As with all materials, the containment is not totally impermeable, but will allow some flow over a

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period of time. Usually cited as the permeability standard is EPA's guidance for hazardous waste landfill barriers, which is less than 1×10^{-7} cm/sec.

The high costs of remediating contaminated sites will force the continuating search for a solution in constructing a bottom barrier. Construction of a containment structure should not be viewed as a final solution, but rather as a part of the remediation system. The barrier may serve only to contain the contaminants until further technological advances provide ways of remediating the site at some point in the future. More often though, the containment is used while some other means of in situ treatment is underway.

Use of a bottom barrier in conjunction with a containment structure offers property owners and environmental engineers a potentially cost-effective management option in situations where alternative remediation options are cost-prohibitive. Current techniques and technologies are now available that can make construction of a bottom barrier a reality. The only step remaining for construction of the bottom barrier is to demonstrate the technologies in the field.

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